Summary of Physics Sensitivities for the FNAL-Homestake VLBNO Experiment

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Abstract

We present a summary of the neutrino fluxes from the various FNAL-Homestake neutrino beamline designs considered for the US Long Baseline Study 2007. In addition we summarize the physics sensitivities that might be achieved at various stages of a FNAL-Homestake neutrino oscillation experiment with a modular massive water Cerenkov detector at Homestake.

I. INTRODUCTION

In May 2007 the US Long Baseline Neutrino Study concluded its year long effort [1] to summarize the status of the proposed next generation of very long baseline neutrino oscillation (VLBNO) experiments. The purpose of this document is to further clarify the beam design options considered for the FNAL-Homestake long baseline experiment and to summarize the physics sensitivities that can be achieved using a staged approach with a modular water Cerenkov detector at Homestake mine.

II. SUMMARY OF BEAM OPTIONS FOR FNAL-HOMESTAKE

The details of the GEANT3 simulation of the NuMI/Homestake beamline, using a wide-band horn and target system [2] can be found here [3]. The simulation used the same software framework and versions used for the NuMI/MINOS beamline [4] simulation in the first MINOS result on ν_μ disappearance [5].The MINOS result demonstrated that the predicted ν_μ flux in the 1-7 GeV region agrees to better 10% with the data from the MINOS near detector. At higher energies the simulation underestimates the neutrino flux by $\approx 20\%$. For the US Long Baseline Study we assumed that the maximum decay tunnel length that can be accomodated on the FNAL site was 400m. Preliminary siting studies conducted in the past few months [6] have indicated that a decay pipe length of up to 627 m can be accomodated on the Fermilab site with the near detector located 400m away from the end of the decay pipe.

A. Neutrino fluxes from various NuMI/Homestake beamline designs

The neutrino total charged current (CC) unoscillated event rate at the far detector from the existing NuMI/MINOS beamline and the proposed NuMI/Homestake beamline is shown in Figure 1. The event rate is shown using an exposure of 10^{21} protons on target to match the NOνA experiment TDR [7]. In a staged FNAL-Homestake experiment with gradual increases in beam power from Fermilab, we have 3 main possible stages: ANU, SNUMI and Project X [8] . ANU will reach 700 kW at proton energies of 120 GeV, SNUMI could reach 1.2 MW at 120 GeV and Project X could reach 2.3 MW for all energies between 60-120 GeV. For the initial ANU or SNUMI stage we propose using the 120 GeV beam for NuMI/Homestake to achieve maximal beam power. In the early stages of the FNAL-Homestake experiment its most likely that the first detector modules will be water Cerenkov, therefore to reduce the NC background in water Cerenkov from the high energy ν's in the 120 GeV beam we have proposed using a slightly off-axis beam at 0.5^0 (the red curve in the right plot of Figure 1). With this off-axis angle, the event rates at the first and second oscillation maxima are slightly higher than the event rate on-axis with a large reduction in event rates from higher energy neutrinos. The off-axis spectrum can be achievable by placing the target and horn assembly off-axis to the 4m diameter decay pipe while keeping the far detector on-axis with the beamline. Another promising development would be to use a (removable) beam plug between the first and second horns during the early stages of the experiment. This option is discussed in the next section . For the later stages of the experiment when the Project X high intensity proton source is available, we also have the capability of selecting the beam energy from 60-120 GeV while maintaining the same power. As shown in Figure 1, for the same beam power the 60 GeV on-axis beam has the same event rate at the 1st and 2nd oscillation maxima as the 120 GeV on-axis beam but lower rates at neutrino energies > 4 GeV. Optimizing the signal to background in the precision stage of the experiment is critical to getting the best sensitivity to CPV. To this end, we have considered physics sensitivities with both the 120 and 60 GeV beam at beam powers of 1-2MW.

We have also considered NuMI/Homestake designs with shorter decay tunnel widths - down to 180m. This may be desirable to keep civil construction costs down. The event rate from NuMI/Homestake using a short 180m decay pipe is shown as the blue histogram in Figure 1. We find the event rate the 1st oscillation maxima is reduced by $> 25\%$ with the shorter beam pipe. More R&D is needed to decide whether the cost savings of a shorter beamline justify the loss in event rate and whether the signal-to-background performance is better than the off-axis approach.

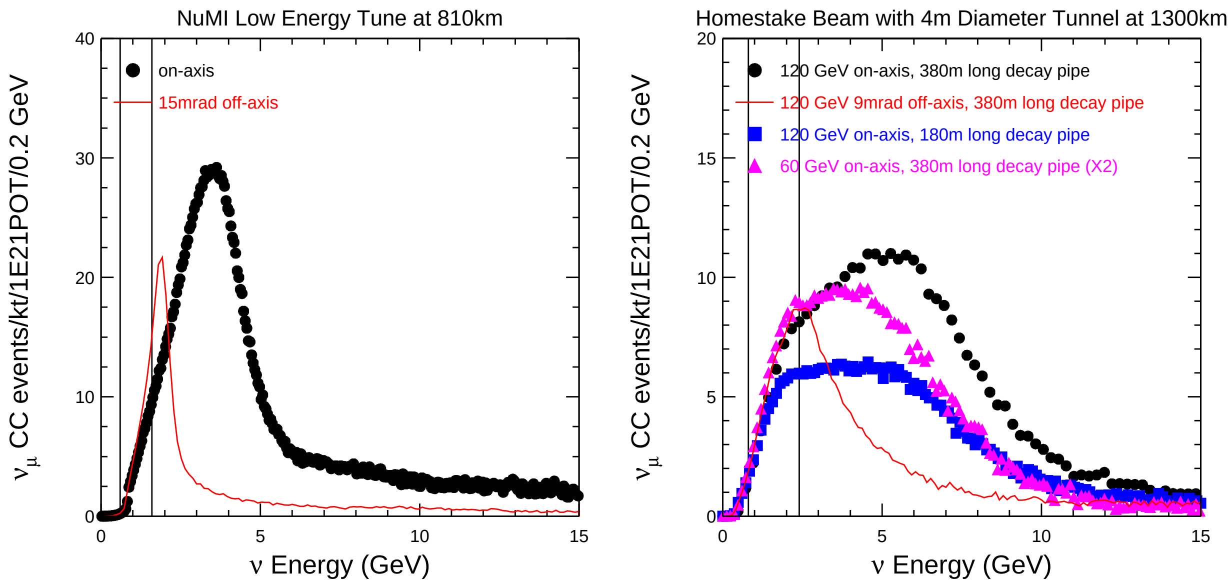

FIG. 1: The total neutrino charged current unoscillated event rate from the NuMI/MINOS beamline with the low energy (LE) tune at 810km (left) and the wide-band NuMI/Homestake beamline at 1300km (right). The two vertical black lines on the plots show the position of the first and second $\nu_\mu \to \nu_e$ oscillation maxima for $\Delta m^2_{31} = 2.5 \times 10^{-3}\mathrm{eV}^2, \delta_{cp} = 0$ with matter effects included. For NuMI/MINOS, the on-axis spectrum is shown as black circles and the off-axis spectrum at the NOνA location (12km or 15mrad off-axis) is shown in red. For the NuMI/Homestake beamline several options are shown, all of which utilize a wide 4m diameter decay pipe. The black circles are the total CC rates from 120 GeV on-axis beam with a 380m long decay pipe. The red histogram is the spectrum from the 120 GeV beam with the 380m long decay tunnel and 9mrad off-axis. The blue histogram is the on-axis spectrum from a 120 GeV beam with a shorter 180m long decay tunnel. The magenta histogram shows the CC spectrum from an on-axis 60 GeV beam with a 380 m decay tunnel. The 60 GeV beam spectrum has been scaled up by a factor of 2 to match the power in the 120 GeV spectra.

TABLE I: Percent change in number of ν_μ interactions in the far detector with different size plugs placed between NuMI/MINOS horn 1 and horn 2 in the LE tune,

Plug configuration			Energy range (GeV)			
Material	Length	Location	0-3	3-6	6-10	10-50
Graphite	1.5m	4m	-7.6%	-2.5%	-26%	-70%
Graphite	2.5m	3.5m	-10%	-3.4%	-41%	-82%
Copper	1.5m	4.0m	-11%	-4.8%	-38%	-85%

B. Proposals for further optimization of the NuMI/Homestake beamline design

To optimize the wide-band NuMI/Homestake beamline design for operation with a large water Cerenkov detector, its highly desirable to suppress the neutrino flux above 6 GeV while preserving the maximal flux from 0-6 GeV. In 2001, a study conducted by Brett Viren of BNL for the NuMI/MINOS beamline [9] indicated that a secondary graphite or copper target, a "beam plug", of 3cm diameter and length 1.5 or 2.5m placed at a distance of 4m or 3.5m respectively from the front face of the first NuMI horn can reduce the number of ν_μ interactions in the far detector in the region with neutrino energies >6 GeV compared to the region < 6 GeV. The effect of the plug on the NuMI LE tune is summarized in Table I

The beam plug option could allow the Homestake water Cerenkov detector to take advantage of the maximal power achievable in the ANU and SNUMI options with the on-axis 120 GeV beam flux while controlling the NC background from the high energy tails. The effect of the beam plug in the wide-band NuMI/Homestake beamline is being evaluated, but is expected to be similar to the NuMI/MINOS beamline simulation results. One possible drawback is the larger reduction in the anti-neutrino rates observed with the beam plug which decreases sensitivity to the mass hierarchy. More optimization studies are needed to decide whether a beam plug, smaller off-axis angle or other targeting designs can further improve the physics sensitivities of a massive water Cerenkov detector with the 120 GeV beam. In addition, the increased cost of adding a beam plug and material R&D for the plug need to be evaluated and taken into account in the final design.

III. PHYSICS SENSITIVITIES ACHIEVABLE AT VARIOUS STAGES OF FNAL-HOMESTAKE VLBNO EXPERIMENT

The physics sensitivities are calculated using an implementation of the SuperK water Cerenkov detector simulation and ν_e event selection [1] in GLoBeS [10]. The details of the sensitivitity calculations are as follows. The fits are always performed to the neutrino and anti-neutrino spectra simultaneously. We also include the disappearance channel which limits the atmospheric oscillation parameters. We build a grid of differences of χ^2 for a range of true $\sin^2 2\theta_{13}$, δ_{cp} and Δm^2 values. The difference is between the hypothesis tested. Afterwards we find the points with the apropriate χ^2 values corresponding to the desired C.L. For each of these true points we generate the expected spectrum and do the following depending on the hypothesis tested:

- Exclusion of $\sin^2\theta_{13}$=0: Fix θ_{13} to 0 and minimize over all other parameters (including δ_{cp}, matter density and systematics) trying to fit the true spectrum. Do this for both the true mass hierarchy and the opposite hierarchy. Take the worst (i.e. lowest) χ^2 of both. This should give the level at which you can exclude θ_{13}=0 including all correlations.

- Mass hierarchy: Fix the mass hierarchy to the opposite of the true value. Minimize over all other parameters (including θ_{13} and δ_{cp}) trying to fit the true spectrum.

- CP violation: Fix δ_{cp} to 0, minimize over all parameters (including θ_{13}) trying to fit the true spectrum. Do the same for $\delta_{cp} = \pi$ and take the worst χ^2. We don't do this test for the wrong hierarchy. Sensitivities are at higher $\sin^2 2\theta_{13}$ for cp violation at the same CL than for determining the mass hierarchy so this should not make a difference (i.e. the true mass hierarchy should always give the worst χ^2).

- The 5%-10% background systematic error is added as a penalty term to the χ^2. The error is fully correlated between bins, i.e. it is a normalization error on the total background rate. The error on the total background is assumed uncorrelated between the neutrino and anti-neutrino runs.

- Systematic errors on the oscillation parameters are also included as penalty terms to the χ^2. We include 5% error on the solar mass splitting, $\sin^2 2\theta_{12}$, and matter density. We also include a systematic uncertainty of 1% on the signal (correlated). We also include current systematic uncertainties on the atmospheric parameters as penalty terms, but our simultaneous fit to the disappearance channel is the more limiting factor.

A. Physics Sensitivities with a 100kT fiducial Water Cerenkov Detector and 700 kW - 1 MW beam

In Stage 1 of a FNAL-Homestake VLBNO experiment, the first water Cerenkov detector module with 100kT fiducial mass will be deployed. Recent studies from K2K [11] indicate that a fidcual cut of 1m from the wall of the water Cerenkov detector is sufficient for long baseline neutrino oscillation physics. For a 100kT fiducial module, this corresponds to a total detector mass of around 120kT (allowing an extra ≈ 0.5 meter for the PMT mounting structure). The first stage of the FNAL-Homestake experiment can be carried out with the 700kW - 1.2MW (at 120 GeV) ANU and SNUMI upgrades to the the existing FNAL accelerator complex. The goal of this stage would be to measure the mass hierarchy should $\sin^2 2\theta_{13}$ be $>= 0.01$. This is the level of sensitivity to $\sin^2 2\theta_{13}$ that will be achieved by the reactor experiments and T2K by 2014. The sensitivities of Stage 1 FNAL-Homestake are shown in Figures 2 and 3. The studies indicate that a 100kT fiducial water Cerenkov detector running for approx 3 yrs in neutrino and 3yrs in anti-neutrino mode with a 1 MW 120 GeV 9mrad off-axis NuMI/Homestake beam can achieve a $> 3\sigma$ sensitivity to the mass hierarchy at values of $\sin^2 2\theta_{13} >= 0.03$ for all values of δ_{cp}. In addition, as shown in Figure 3 there is also some sensitivity to CPV at the 3σ level for values of $\sin^2 2\theta_{13}$ down to 0.03.

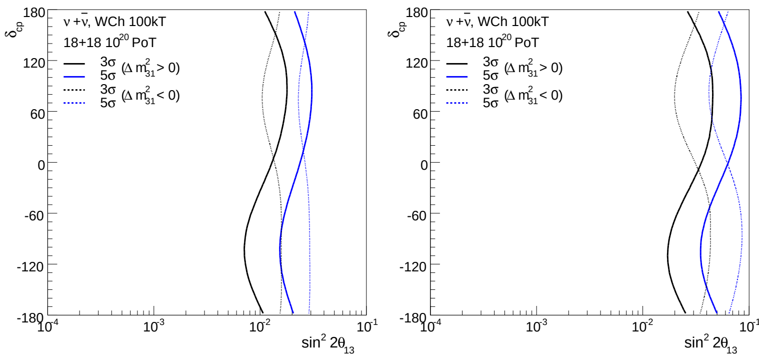

FIG. 2: Sensitivity with 100kT fiducial, 700kW running for 2.6+2.6yrs. 120 GeV, 9mrad off-axis NuMI/Homestake beam with a decay tunnel 4m in diameter, 380m in length. 5% systematic on the background.

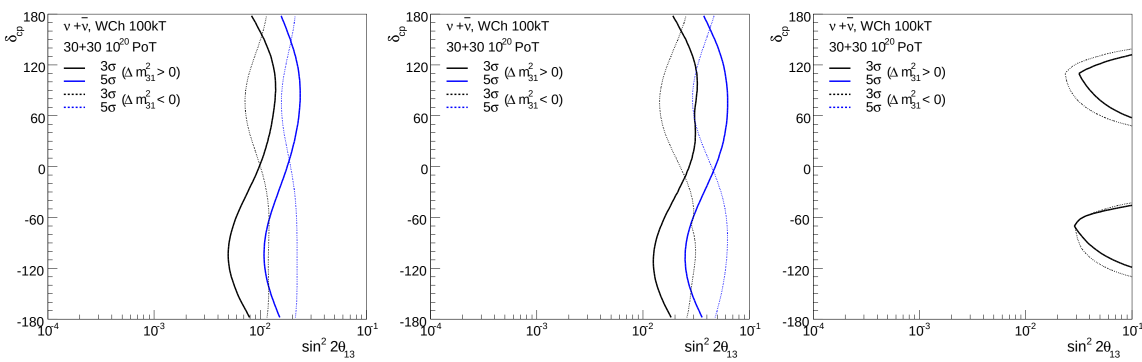

FIG. 3: Sensitivity with 100kT fiducial, 1MW running for 3+3yrs. 120 GeV, 9mrad off-axis NuMI/Homestake beam with a decay tunnel 4m in diameter, 380m in length. 5% systematic on the background

B. Physics Sensitivities with a 300kT fiducial Water Cerenkov Detector and 1 - 2 MW beam

In the later stages of a FNAL-Homestake experiment, the emphasis will be on either pushing the sensitivity to $\sin^2 2\theta_{13}$ an order of magnitude beyond the reach of the upcoming reactor and accelerator experiments down to $\sin^2 2\theta_{13} \sim 0.001$ or to be able to measure the hierarchy and δ_{cp} down to values of $\sin^2 2\theta_{13} \sim 0.01$. To push the sensitivity much beyond these levels is probably not achievable in a long baseline neutrino experiment utilizing conventional horn focused neutrino beams (which have irreducible ν_e backgrounds at the 1% level) and would most probably require a neutrino factory. In later stages of the experiment the detector will have been upgraded to include more 100kT water Cerenkov detector modules (at least 3) and perhaps a massive LAr detector as well. In addition the Project X NuMI/Homestake beamline will be able to deliver a beam power of up to 2.3 MW for 60-120 GeV proton beam energies. Figures 4 and 6 demonstrate the sensitivities achievable with the full scale FNAL-Homestake experiment with 3 100kT water Cerenkov modules coupled with a 1-2MW beam.

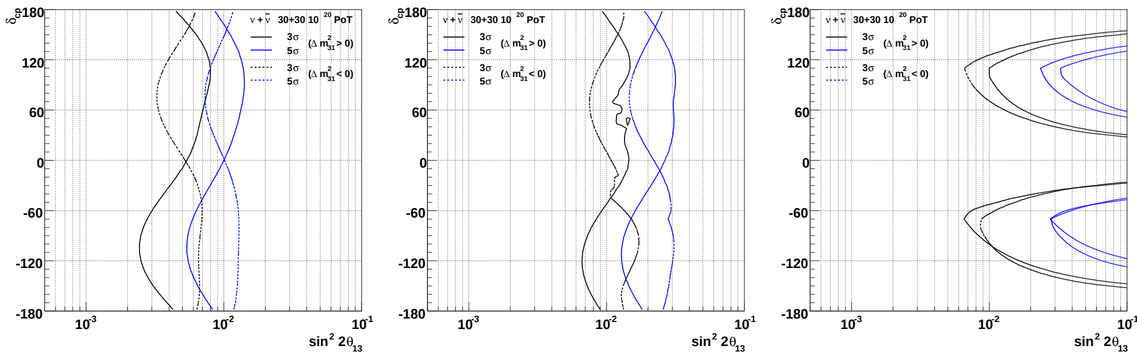

FIG. 4: Sensitivity with 300kT fiducial, 1MW running for 3+3yrs. 120 GeV, 9mrad off-axis NuMI/Homestake beam with a decay tunnel 4m in diameter, 380m in length. 5% bkgd systematic.

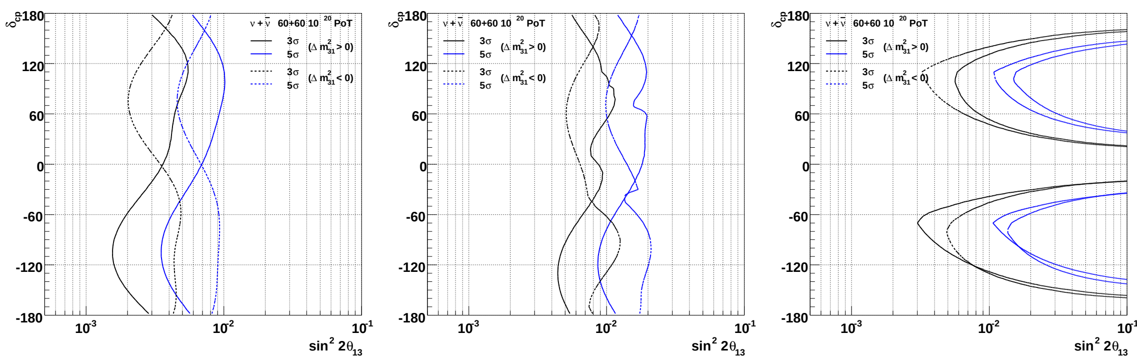

FIG. 5: Sensitivity with 300kT fiducial, 2MW running for 3+3yrs. 120 GeV, 9mrad off-axis NuMI/Homestake beam with a decay tunnel 4m in diameter, 380m in length. 5% bkgd systematic

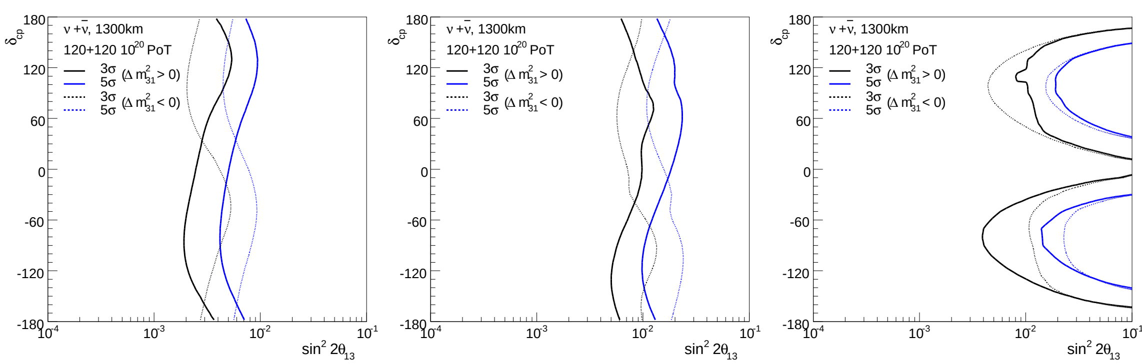

FIG. 6: Sensitivity with 300kT fiducial, 2MW running for 3+3yrs. 60 GeV, on-axis NuMI/Homestake beam with a decay tunnel 4m in diameter, 380m in length. 5% bkgd systematic

C. Summary of Physics Sensitivities

Table II summarizes the sensitivities of the proposed FNAL-Homestake VLBNO experiment with a massive water Cerenkov detector for different wide-band beams, exposure, and detector sizes shown in previous sections. We conclude that ultimately there is little difference between the performance of the 60 GeV on-axis and 120 GeV 9mrad off-axis beam. The latter beam has lower signal statistics but better signal:background peformance. Figures 7 and 8 demonstrate the ability of the FNAL-Homestake VLBNO experiment to accurately measure the values of $\sin^2 2\theta_{13}$ and δ_{cp} at different stages of the experiment.

TABLE II: Sensitivities of the proposed FNAL-Homestake VLBNO experiment with a massive water Cerenkov detector for different wide-band beams, exposure, and detector sizes. The decay pipe for all beam options is 4m in diameter and 380m in length with the same target and horn design as in [2]. For $\sin^2 2\theta_{13}$ and the mass hierarchy the sensitivity is given as the minimum value of $\sin^2 2\theta_{13}$ at which the experiment achieves 3σ reach for all δ_{cp}. For CPV the sensitivity is given as the minimum value of $\sin^2 2\theta_{13}$ at which the experiment achieves 3σ reach for 50% δ_{cp}. The uncertainties are 5% or 10% syst uncertainty on bkgd, a few% uncertainty on other osc parameters, and 1% syst signal uncertainty. 1yr = 2×10^7 seconds $\Rightarrow$ 1MW.yr = 10E20 POT at 120 GeV and 20E20 POT at 60 GeV.

Beam	Det size (FIDUCIAL)	Exposure $\nu + \bar{\nu}$	syst. uncert on bkgd	$\sin^2 2\theta_{13}$	sign(Δm^2_{31})	CPV
NuMI/HStake	100kT	700kW 2.6+2.6yrs	5%	0.018	0.044	> 0.1
120 GeV	100kT	1MW 3+3yrs	5%	0.014	0.031	> 0.1
9mrad off-axis	300kT	1MW 3+3yrs	5%	0.008	0.017	0.025
	300kT	1MW 3+3yrs	10%	0.009	0.018	0.036
	300kT	2MW 3+3yrs	5%	0.005	0.012	0.012
	300kT	2MW 3+3yrs	10%	0.006	0.013	0.015
NuMI/HStake	100kT	1MW 3+3yrs	5%	0.012	0.037	>0.1
60GeV on-axis	300kT	1MW 3+3yrs	10%	0.008	0.021	0.037
	300kT	2MW 3+3yrs	5%	0.005	0.013	0.015

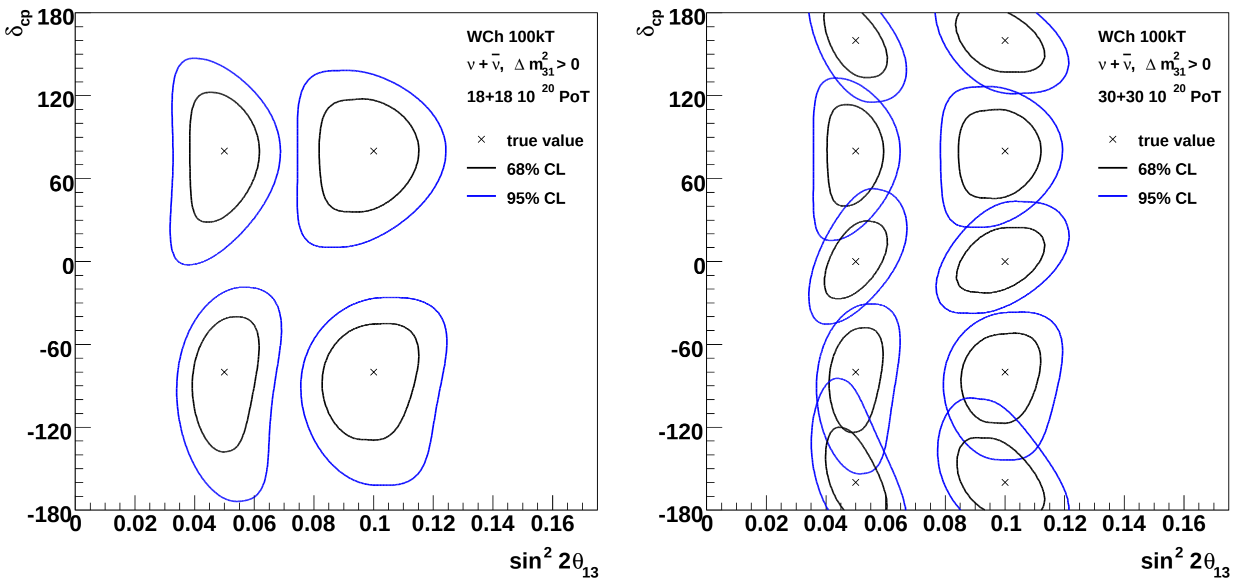

FIG. 7: Measurement of δ_{cp} and $\sin^2 2\theta_{13}$ with a 100kT fiducial detector in a 120 GeV 9mrad off-axis wide-band beam. The exposures assumed are a 700kW 2.6+2.6 yrs (left), and 1MW 3+3 yrs (right). Normal hierarchy and 5% bkgd systematic assumed.

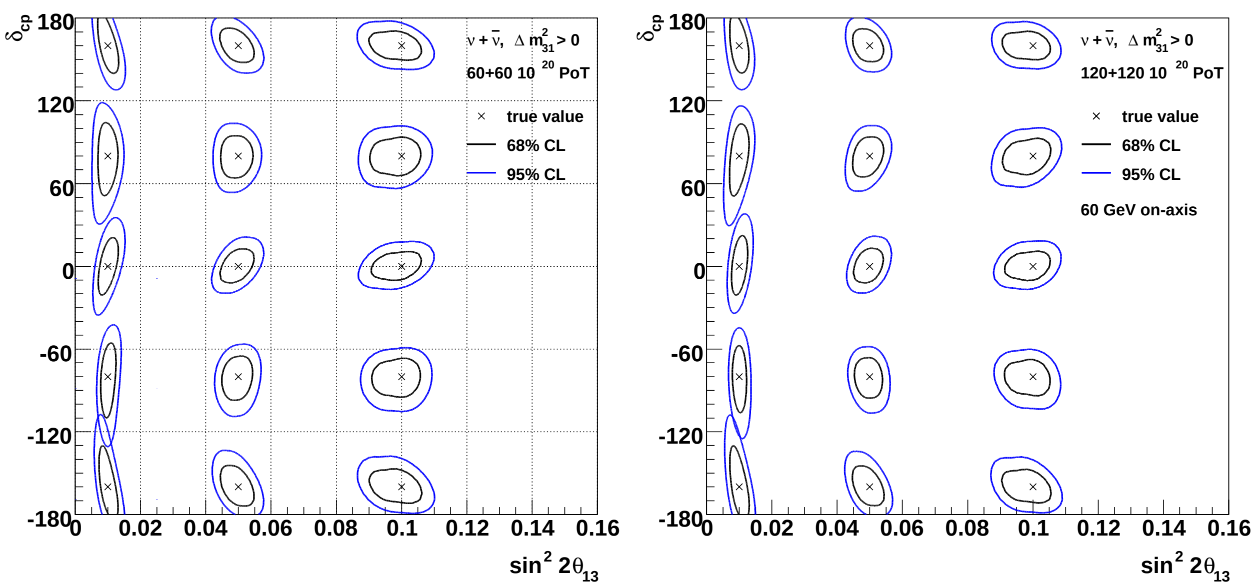

FIG. 8: Measurement of δ_{cp} and $\sin^2 2\theta_{13}$ with a 300kT fiducial detector with a 2MW beam 3+3 yrs. The left plot is for the 120 GeV 9mrad off-axis wide-band beam and the right plot is for a 60 GeV on-axis wide-band beam. Normal hierarchy and 5% bkgd systematic are assumed.

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